



Mirror dark matter cosmology – predictions for $N_{\text{eff}}[\text{CMB}]$ and $N_{\text{eff}}[\text{BBN}]$

R. Foot

ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, University of Melbourne, Victoria 3010, Australia

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ABSTRACT

Mirror dark matter interacting with ordinary matter via photon-mirror photon kinetic mixing can explain the DAMA, CoGeNT and CRESST-II direct detection experiments. This explanation requires kinetic mixing of strength $\epsilon \sim 10^{-9}$. Such kinetic mixing will have important implications for early Universe cosmology. We calculate the additional relativistic energy density at recombination, $\delta N_{\text{eff}}[\text{CMB}]$. We also calculate the effects for big bang nucleosynthesis, $\delta N_{\text{eff}}[\text{BBN}]$. Current hints that both $\delta N_{\text{eff}}[\text{CMB}]$ and $\delta N_{\text{eff}}[\text{BBN}]$ are non-zero and positive can be accommodated within this framework if $\epsilon \approx \text{few} \times 10^{-9}$. In the near future, measurements from the Planck mission will either confirm these hints or constrain $\epsilon \lesssim 10^{-9}$.

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The long standing DAMA annual modulation signal [1], along with more recent data from the CoGeNT [2] and CRESST-II [3] experiments can be explained within a simple hidden sector framework [4,5] (see also Refs. [6,7] for earlier studies). The requirement is for a hidden sector with an unbroken $U(1)'$ interaction kinetically mixed with the standard $U(1)_Y$ gauge field. Such a framework can explain all of the direct detection results, both positive and negative, provided that the hidden sector contains two or more stable particles. Mirror dark matter [8] appears to be the most well motivated and also constrained example of such a theory (see Ref. [9] for reviews and more comprehensive references). In the mirror dark matter theory, the hidden sector is exactly isomorphic to the ordinary sector except the chiralities are interchanged. In this case an exact unbroken mirror symmetry can be defined which interchanges each ordinary particle with a mirror partner, as well as mapping $x, t \rightarrow -x, t$ [8]. The latter property allows mirror symmetry to be identified with space–time parity which provides an interesting theoretical motivation for such a theory.¹

In this theory dark matter consists of a spectrum of stable mirror particles of known masses (e' , H' , He' , O' , ...) which interact with the ordinary particles via gravity and renormalizable photon-mirror photon kinetic mixing: [12]²

$$\mathcal{L}_{\text{mix}} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} \quad (1)$$

where $F_{\mu\nu}$ is the ordinary photon field strength tensor, and $F'_{\mu\nu}$ is the field strength tensor for the mirror photon. This interaction enables mirror charged particles, such as e' , p' , to couple to ordinary photons with electric charge ϵe [14].

Studies have shown [15] that mirror dark matter can provide a successful account of the Large Scale Structure (LSS) of the Universe which can mimic cold dark matter or warm dark matter, depending on initial conditions. Mirror dark matter, though, has quite distinctive properties on smaller scales. Observations suggest that: a) In galaxy clusters or at least in some of them, mirror dark matter should be predominately confined within galactic halos to account for the observations of the Bullet cluster [16] (cf. [17]). b) Within galactic halos, limits on the MACHO fraction [18] suggest that mirror dark matter is mainly (at least $\sim 50\%$) in gaseous form – i.e. an ionized plasma comprising e' , H' , He' , O' , ... A substantial MACHO fraction is also possible [19]. Mirror dark matter is dissipative, which indicates that a substantial heat source should exist to replace the energy lost due to radiative cooling. It turns out that ordinary supernova can supply the required energy to stabilize the mirror dark matter halo provided that $\epsilon \sim 10^{-9}$ [20]. This heat source is anisotropic in spiral galaxies (given that the supernova originate predominately from the disk) which might explain the deviations from perfect spherical halos which are necessary to agree with observations. c) The self-interactions of mirror dark matter within galactic halos might help explain the inferred cored dark matter distribution – a long standing puzzle of the standard cold dark matter paradigm.

The gaseous component of the halo is presumed to be composed of an ionized plasma comprising a spectrum of components

¹ E-mail address: rfoot@unimelb.edu.au.

² There are also interesting models with mirror symmetry spontaneously broken, see e.g. [10,11].

³ Other interactions are possible including a Higgs-mirror Higgs coupling $\lambda \phi^\dagger \phi \phi'^\dagger \phi'$, which can lead to novel effects for Higgs physics that can be probed at the LHC [13].

e' , H' , He' , O' , These components can potentially be detected in direct detection experiments via the kinetic mixing interaction, Eq. (1), which induces spin-independent elastic Rutherford scattering. The H' , He' components, which are naively expected to be dominant, are however very light. In fact these components are so light that they are unable to explain the DAMA, CoGeNT or CRESST-II signals. The experiment most sensitive to the He' component turns out to be the earlier CRESST/Sapphire experiment [21]. That experiment can be used to infer the bound: [6]

$$\epsilon \sqrt{\xi_{He'}} \lesssim 3 \times 10^{-9}. \quad (2)$$

The on-going Texono experiment [22] at Jin-Ping underground laboratory is expected to provide a much more sensitive probe of the He' component in the near future. The remaining heavier components, are for simplicity assumed to be composed of a 'dominant' metal component, A' . The direct detection experiments, DAMA, CoGeNT and CRESST-II can be explained by the A' component if [4,5]:

$$\begin{aligned} \epsilon \sqrt{\xi_{A'}} &\sim \text{few} \times 10^{-10}, \\ \frac{m_{A'}}{m_p} &\approx 16\text{--}56 \end{aligned} \quad (3)$$

where $\xi_{A'} \equiv n_{A'} m_{A'}/(0.3 \text{ GeV}/\text{cm}^3)$ is the halo mass fraction of the species A' and m_p is the proton mass. Combining Eq. (2) and Eq. (3), we obtain a lower limit on the ratio $\xi_{A'}/\xi_{He'} \gtrsim 10^{-2}$ at the Earth's location in the halo. This appears to be a relatively high metal component, and might be due to rapid mirror star formation and evolution at an early epoch [23]. It might also be possible to produce the metal component in the early Universe, although this is disfavored in the simplest scenarios with high reheating temperature [24]. Allowing for possible uncertainties in $\xi_{A'}$, Eq. (3) suggests that ϵ should be in the range:

$$10^{-10} \lesssim \epsilon \lesssim 10^{-8}. \quad (4)$$

This range of ϵ is consistent with the direct laboratory limits, the most stringent of which arises from invisible decays of orthopositronium [25,26], $\epsilon \lesssim 1.5 \times 10^{-7}$. An important proposal exists [27] for a more sensitive orthopositronium experiment which can cover much of the ϵ range of interest, Eq. (4).³

In the context of early Universe cosmology, the kinetic mixing can induce processes which transfer energy into the mirror sector. This will lead to various modifications to big bang nucleosynthesis (BBN), Cosmic Microwave Background anisotropies (CMB) and also Large Scale Structure (LSS). This allows values of $\epsilon \gtrsim 10^{-9}$ to be probed in early Universe cosmology.

Recall that the relativistic energy component at recombination can be parameterized in terms of the effective number of neutrino species, $N_{\text{eff}}[\text{CMB}]$, by:

$$\rho_{\text{rad}} = \left(1 + \frac{7}{8} \left[\frac{4}{11}\right]^{4/3} N_{\text{eff}}[\text{CMB}]\right) \rho_\gamma \quad (5)$$

where ρ_γ is the energy density of the CMB photons. In the standard electroweak theory, $N_{\text{eff}} \simeq 3.046$ (the difference from 3 being due to slight heating of the neutrinos from $\bar{e}e$ annihilation) [30]. Currently there are some interesting hints that $\delta N_{\text{eff}}[\text{CMB}] \equiv N_{\text{eff}}[\text{CMB}] - 3.046$ is in fact non-zero and positive within the usual ΛCDM framework. For example, the Wilkinson Microwave Anisotropy Probe (WMAP) obtained $N_{\text{eff}}[\text{CMB}] =$

4.34 ± 0.87 (1σ C.L.) [31]. Observations with the Atacama Cosmology Telescope suggest $N_{\text{eff}}[\text{CMB}] = 4.56 \pm 0.75$ (1σ C.L.) [32]. Also, results of the South Pole Telescope combined with WMAP7 suggest $N_{\text{eff}}[\text{CMB}] = 3.86 \pm 0.42$ (1σ C.L.) [33]. A recent analysis [34] combining the data finds that:

$$N_{\text{eff}}[\text{CMB}] = 4.08^{+0.71}_{-0.68} \quad \text{at } 95\% \text{ C.L.} \quad (6)$$

An effective neutrino number can also be defined for BBN, and it is worth noting that two recent measurements [35,36] of Y_p suggest $N_{\text{eff}}[\text{BBN}] > 3$. These results have motivated a number of proposals for new physics, including models with sterile neutrinos [37]. Importantly, high precision results from the Planck mission should be able to confirm a non-zero $\delta N_{\text{eff}}[\text{CMB}]$ to within a precision of around 0.2 [38] in the near future. In the meantime, it is timely to work out the predictions for $N_{\text{eff}}[\text{CMB}]$ and $N_{\text{eff}}[\text{BBN}]$ in the mirror dark matter model.

In the $\epsilon \rightarrow 0$ limit, the ordinary and mirror particles decouple from each other, and in general they may have different temperatures, T , T' . It will be useful to define the temperatures: T_γ [T'_γ] for the temperature of the ordinary [mirror] photons and T_ν [T'_ν] is the temperature of the ordinary [mirror] neutrinos. In this study, we assume the initial conditions $T'_\gamma, T'_\nu \ll T_\gamma = T_\nu$ due to some physics at early times. [This is reasonable given alternative initial conditions, such as $T'_\gamma, T'_\nu \approx T_\gamma, T_\nu$ are excluded by BBN, CMB.] Asymmetric reheating within inflationary scenarios is one possibility [39]. If we assume that only the ordinary matter is reheated after inflation, then we have the initial condition $T'_\gamma, T'_\nu \simeq 0$ and $T_\gamma = T_\nu = T_{\text{RH}}$. With these initial conditions it is always safe to ignore T'_ν since $T'_\nu \ll T'_\gamma$ in the period of interest. This is because T'_γ/T_γ generation occurs mainly in the low temperature region, $T \lesssim \text{few MeV}$, where the mirror weak interaction rate is always much less than the expansion rate: $G_F^2 T'^5 \ll T^2/m_{\text{pl}}$.

For $T_\gamma < 100 \text{ MeV}$, $\bar{e}e \rightarrow \bar{e}'e'$ is the dominant process which transfers energy into the mirror sector. This process will not only generate T'_γ but will also slightly reduce T_γ . This energy transfer happens predominately after the kinetic decoupling of the neutrinos (i.e. for $T_\gamma \lesssim 3 \text{ MeV}$), so the effect is to slightly decrease T_γ/T_ν . Therefore, at recombination the energy density of neutrinos will be larger than it would otherwise have been if there were no kinetic mixing. This effect will contribute to $\delta N_{\text{eff}}[\text{CMB}]$ along with the more obvious contribution to $\delta N_{\text{eff}}[\text{CMB}]$ from the increase in energy density due to the production of the mirror photons. We will see that these two contributions are numerically similar in magnitude.

The cross-section for the process $\bar{e}e \rightarrow \bar{e}'e'$ is:

$$\sigma = \frac{4\pi}{3} \alpha^2 \epsilon^2 \frac{1}{s^3} (s + 2m_e^2)^2 \quad (7)$$

where s is the usual Mandelstam variable and m_e is the electron mass. The energy transfer to the mirror sector within a co-moving volume, R^3 , per unit time is:

$$\frac{dQ}{dt} = R^3 n_{e^+} n_{e^-} \langle \sigma v_{\text{Mol}} \mathcal{E} \rangle \quad (8)$$

where \mathcal{E} is the energy transferred in the process $\bar{e}e \rightarrow \bar{e}'e'$, v_{Mol} is the Møller velocity (see e.g. Ref. [40]), and $n_{e^-} \simeq n_{e^+}$ is the number density of electrons:

$$n_{e^-} = \frac{1}{\pi^2} \int_{m_e}^{\infty} \frac{\sqrt{E^2 - m_e^2} E}{1 + \exp(E/T_\gamma)} dE. \quad (9)$$

The quantity $\langle \sigma v_{\text{Mol}} \mathcal{E} \rangle$ is given by [41] (see also Ref. [40]):

³ There are a number of other possible implications of kinetic mixing, for example if the solar system contains mirror matter space-bodies [28], see also the review [29].

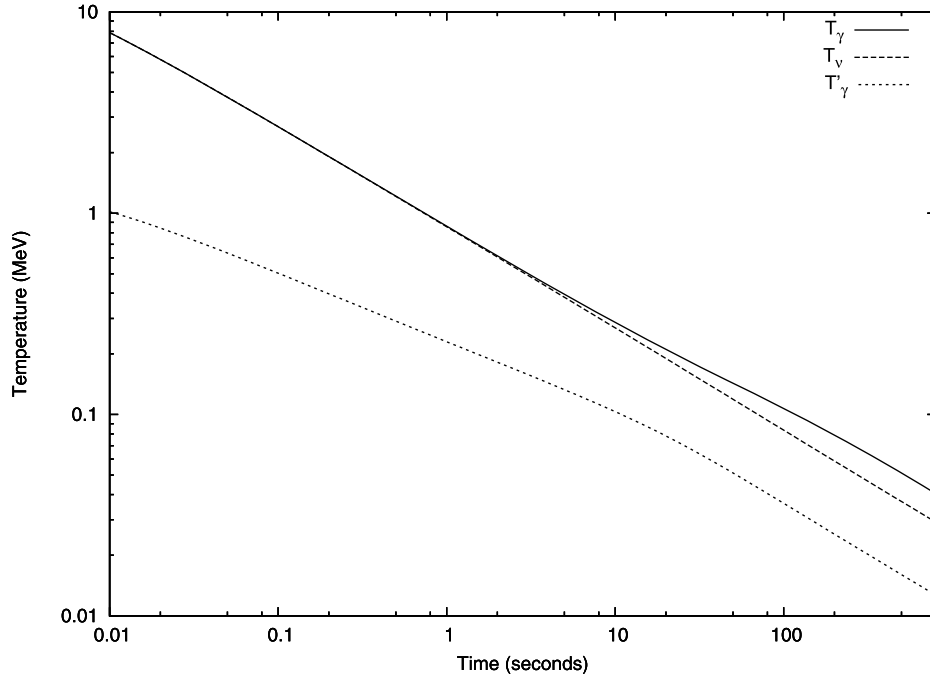


Fig. 1. Evolution of T_γ (solid line), T_ν (dashed line) and T'_γ (dotted line) for $\epsilon = 10^{-9}$.

$$\langle \sigma v_{M\theta l \mathcal{E}} \rangle = \frac{\omega}{8m_e^4 T_\gamma^2 [K_2(m_e/T_\gamma)]^2} \int_{4m_e^2}^{\infty} ds \sigma(s - 4m_e^2) \times \sqrt{s} \int_{\sqrt{s}}^{\infty} dE_+ e^{-E_+/T_\gamma} E_+ \sqrt{\frac{E_+^2}{s} - 1} \quad (10)$$

where K_2 is the modified Bessel function of order 2. The quantity $\omega \approx 0.8$ takes into account various approximations in deriving Eq. (10) such as replacing the exact Fermi–Dirac distribution of \bar{e} , e with the simpler Maxwellian one [41].

Energy is transferred from the ordinary particles to the mirror particles. The second law of thermodynamics can be used to work out the change in entropy of the ordinary particles:

$$dS = \frac{-dQ}{T_\gamma}. \quad (11)$$

To a very good approximation, we can neglect the contribution of the neutrinos to dS since energy is mostly transferred to the mirror sector after neutrino kinetic decoupling (i.e. for $T_\gamma \lesssim 3$ MeV). Thus, $R \propto 1/T_\nu$, and the above equation has the form:

$$\frac{d}{dt} \left[\frac{(\rho_\gamma + p_\gamma + \rho_e + p_e)R^3}{T_\gamma} \right] = -\frac{n_e - n_{e^+} \langle \sigma v_{M\theta l \mathcal{E}} \rangle R^3}{T_\gamma} \quad (12)$$

where

$$\begin{aligned} \rho_\gamma &= \frac{\pi^2}{15} T_\gamma^4, \\ p_\gamma &= \frac{\rho_\gamma}{3}, \\ \rho_e &= \frac{2T_\gamma^4}{\pi^2} \int_x^\infty \frac{(u^2 - x^2)^{1/2} u^2}{1 + e^u} du, \\ p_e &= \frac{2T_\gamma^4}{3\pi^2} \int_x^\infty \frac{(u^2 - x^2)^{3/2}}{1 + e^u} du \end{aligned} \quad (13)$$

and $x = m_e/T_\gamma$. The entropy gained by the mirror particles is:

$$dS = \frac{dQ}{T'_\gamma}. \quad (14)$$

This equation implies that

$$\frac{d}{dt} \left[\frac{(\rho'_\gamma + p'_\gamma + \rho'_e + p'_e)R^3}{T'_\gamma} \right] = \frac{n_e - n_{e^+} \langle \sigma v_{M\theta l \mathcal{E}} \rangle R^3}{T'_\gamma} \quad (15)$$

where

$$\begin{aligned} \rho'_\gamma &= \frac{\pi^2}{15} T_\gamma'^4, \\ p'_\gamma &= \frac{\rho'_\gamma}{3}, \\ \rho'_e &= \frac{2T_\gamma'^4}{\pi^2} \int_{x'}^\infty \frac{(u^2 - x'^2)^{1/2} u^2}{1 + e^u} du, \\ p'_e &= \frac{2T_\gamma'^4}{3\pi^2} \int_{x'}^\infty \frac{(u^2 - x'^2)^{3/2}}{1 + e^u} du \end{aligned} \quad (16)$$

and $x' = m_e/T'_\gamma$. The Friedmann equation reads:

$$\left(\frac{\dot{R}}{R} \right)^2 = \frac{8\pi}{3m_{pl}^2} [\rho_\gamma + \rho_e + \rho_\nu + \rho'_\gamma + \rho'_e] \quad (17)$$

where $m_{pl} \simeq 1.22 \times 10^{22}$ MeV is the Planck mass. The energy density of the neutrinos is given by the standard value, $\rho_\nu = \frac{7\pi^2}{40} T_\nu^4$. Eqs. (12), (15) and Eq. (17) form a closed system which can be solved to give the evolution of T_γ , T_ν and T'_γ . By way of example, the result for $\epsilon = 10^{-9}$ is shown in Fig. 1.

We find numerically that T'_γ/T_γ evolves to a constant which satisfies:

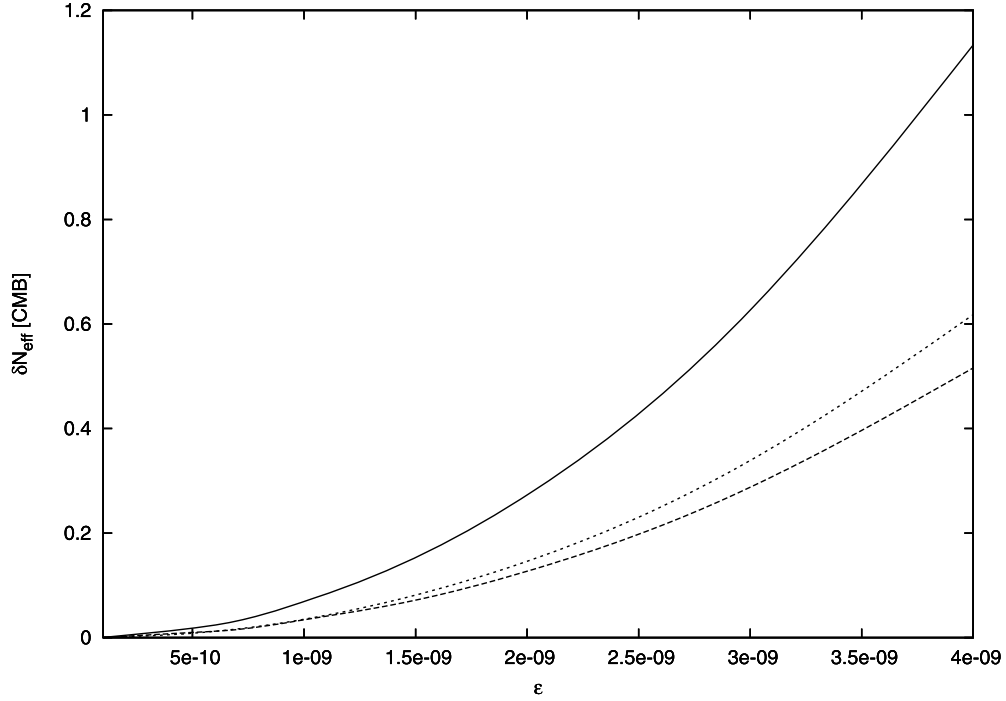


Fig. 2. $\delta N_{\text{eff}}[\text{CMB}]$ versus ϵ (solid line). The separate contributions, discussed in the text, δN_{eff}^a (dashed line) and δN_{eff}^b (dotted line) are also shown.

$$\frac{T'_\gamma}{T_\gamma} \simeq 0.31 \left(\frac{\epsilon}{10^{-9}} \right)^{1/2} \quad (18)$$

which is consistent with the results of the earlier study [41].

The energy density of the relativistic components at recombination can be expressed in terms of an effective neutrino number, Eq. (5). The change in this effective neutrino number due to the kinetic mixing effect, $\delta N_{\text{eff}}[\text{CMB}]$, can be computed as follows:

$$\delta N_{\text{eff}}[\text{CMB}] = 3 \left(\left[\frac{T_\nu(\epsilon)}{T_\nu(\epsilon=0)} \right]^4 - 1 \right) + \frac{8}{7} \left(\frac{T'_\gamma(\epsilon)}{T_\nu(\epsilon=0)} \right)^4 \quad (19)$$

where the temperatures are evaluated at the time when photon decoupling occurs, i.e. when $T_\gamma = T_{\text{dec}} = 0.26$ eV. The first term on the right-hand side, δN_{eff}^a , is the contribution due to the photon cooling, which increases the relative energy density of the neutrinos. The second term, δN_{eff}^b , is the contribution to the energy density from the mirror photons. In Fig. 2 we plot $\delta N_{\text{eff}}[\text{CMB}]$ versus ϵ , showing also the separate contributions δN_{eff}^a and δN_{eff}^b . As remarked earlier [see the discussion around Eq. (6)] there are current hints that $\delta N_{\text{eff}}[\text{CMB}]$ is non-zero and positive. Indeed, the result of the combined analysis [34], Eq. (6), provides an interesting hint that $\epsilon \approx \text{few} \times 10^{-9}$.

Previous studies [15] based on successful LSS have suggested that T'_γ/T_γ should obey an upper limit of around 0.3. As pointed out previously [41], Eq. (18) then suggests an upper limit on ϵ of around $\epsilon \lesssim 10^{-9}$. However due to the complexity of modeling the effects of mirror dark matter for LSS there is a significant uncertainty (maybe even a factor of two or so) in the limit on T'_γ/T_γ from the existing studies based on LSS considerations, and thus a more conservative upper limit on ϵ is likely to be around $\epsilon \lesssim 4 \times 10^{-9}$. Obviously if the Planck mission confirms the current hints that $\delta N_{\text{eff}}[\text{CMB}] > 0$, then this would warrant a careful re-analysis of the LSS implications of the mirror dark matter theory.

The transfer of energy into the mirror sector also affects BBN as first pointed out in Ref. [42]. The effect on the primordial He-

lium abundance can easily be obtained by computing Y_p in the usual way, but with the T_γ, T_ν dependent rates: $n + \bar{e} \leftrightarrow p + \bar{\nu}_e$, $n + \nu_e \leftrightarrow p + e$, $n \leftrightarrow p + e + \bar{\nu}_e$ evolved down to the deuterium ‘bottle neck’ temperature $T_\gamma = 0.07$ MeV obtained by utilizing the solution of Eqs. (12), (15) and Eq. (17).⁴ In this way we can compute the helium mass fraction for a particular value of ϵ , $Y_p(\epsilon)$. For $\epsilon = 0$, the result is the standard value, $Y_p(0) \simeq 0.24$. We define $\delta N_{\text{eff}}[\text{BBN}]$ in the usual way:

$$\delta N_{\text{eff}}[\text{BBN}] = \frac{Y_p(\epsilon) - Y_p(0)}{0.013}. \quad (20)$$

Thus $\delta N_{\text{eff}}[\text{BBN}] = 1$ corresponds to an increase of Y_p of 0.013 which is equivalent to having 4 neutrinos instead of 3 contributing to the energy density. In Fig. 3 we plot our results for $\delta N_{\text{eff}}[\text{BBN}]$ versus ϵ . Comparison of Fig. 3 with Fig. 2 shows that we expect $\delta N_{\text{eff}}[\text{CMB}] > \delta N_{\text{eff}}[\text{BBN}]$. The diminished effect for BBN is simply because a significant part of the generation of T'_γ and reduction of T_γ/T_ν occurs below the freeze out temperature of weak interactions $T_w \approx 0.8$ MeV.

In conclusion, we have computed the additional radiation content of the Universe at the recombination epoch due to the effects of photon-mirror photon kinetic mixing, $\delta N_{\text{eff}}[\text{CMB}]$. We have also calculated the effects for big bang nucleosynthesis, $\delta N_{\text{eff}}[\text{BBN}]$. There are some interesting hints that both $\delta N_{\text{eff}}[\text{CMB}]$ and $\delta N_{\text{eff}}[\text{BBN}]$ are non-zero and positive, which if confirmed by e.g. the anticipated high precision measurements of the CMB from the Planck mission, will ultimately allow ϵ to be determined.

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⁴ BBN implications of mirror dark matter without kinetic mixing, but with non-zero T'/T arising from assumed initial conditions was studied in Ref. [43].

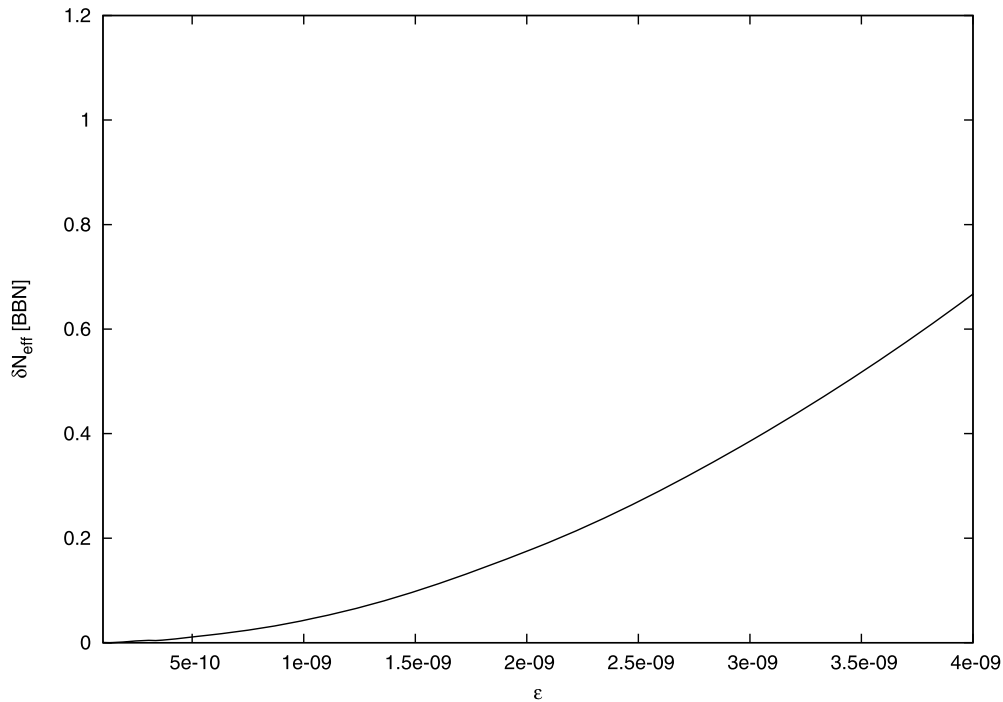


Fig. 3. δN_{eff} [BBN] versus ϵ .

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